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ORIGINAL PAPER

Spatial and temporal variations of soil moisture in three types of agroforestry boundaries in the Loess Plateau, China

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Abstract: Agroforestry is a ubiquitous landscape on the slopes in Loess Plateau, where soil moisture is a limiting factor for plant growth and development. The spatial and temporal characteristics of soil moisture were studied in three types of agroforestry boundaries: forest-grassland, forest-cropland and shelterbelt-cropland. The result shows that soil moisture content decreased with soil depth increasing from the surface to 110 cm. Soil moisture content differed significantly among the three boundaries all in the rainy season (July–September), dry season (May–June) and spring (March–April). The horizontal distribution of soil moisture in different soil layers in the three types of boundaries showed different patterns with line form, wave form, scoop form or "W" form. The distance of edge influence (DEI) of soil moisture in different types of landscape boundaries was estimated by variance analysis and multiple comparisons. In dry season the DEI in 0–10 cm soil layer was 0.4 H (H, average height of trees), which ranged from 0.2 H in grassland or in cropland to 0.2 H in forest field for both forest-grassland and forest-cropland boundaries, and 0.7 H (ranged from 0.2 H in cropland to 0.5 H in forest field) for shelterbelt-cropland boundary. In rainy season the DEI at soil depth of 0–110 cm was 0.7 H for the three boundaries. The results indicated that agroforestry type should be carefully selected to maintain soil moisture in land management, especially in restoring degraded land in Loess Plateau.

Keywords: distance of edge influence; forest-grassland system; land use; soil moisture

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Introduction

Centuries of deforestation and over-grazing have resulted in the degraded ecosystems in the Loess Plateau in north-central China. Soil erosion with heavy summer precipitation becomes a serious problem to the further land degradation and the Yellow River water pollution. Therefore, land managers face a great challenge on ecosystem restoration, especially on vegetation recovery. Over the last several decades, Chinese goverment launched several ecological programs to increase vegetation coverage in this region. Because of the low water-holding capacity and high evaporation of loess soil, soil moisture is the most important controlling factor on vegetation establishment (Qiu et al. 2001; Liu et al. 2003). Yet, the patterns of soil moisture in agroforestry systems are not well understood. Many studies have investigated the soil moisture distribution in different ecosystems such as forest, grassland and cropland (Famiglietti and Wood 1995; English et al. 2005; Das and Mohanty 2008), and the patterns within a single ecosystem have been well defined (Farahani and Bausch 1995; Wang et al. 2004; Ingmar et al. 2003; Huo et al. 2008). However, few studies were conducted on soil moisture distribution characteristics of ecotone between ecosystems (You et al. 2005).

Agroforestry is any type of land use approach or system in which woody perennials are deliberately grown on the same land management unit as annual crops and/or animal using a specified spatial and temporal order (Gholz 1987; Liu et al. 2004). Chisci et al. (2001) observed that agroforestry system improved soil physical characteristics (such as the mean weight diameter of stable soil aggregates and total soil porosity from 1 to 6 mm) and

provided environmental protection by controlling runoff and reducing soil erosion on the slope. Meng et al. (1995) showed that shelterbelt-pear-crop intercropping increased soil moisture content by 14% in the 0–40 cm soil depth compared to crop-only treatment. Boundaries are important components of spatially heterogeneous areas, existing between different habitats and across a broad range of scales (Cadenasso et al. 2003); they are "semipermeable membranes" among different homogeneous landscapes, controlling the conveyance of biotic and abiotic elements between two completely different landscapes (Weins 1989). Boundary is an important component of spatial heterogeneous zones (Fagan et al. 2003; Strayer et al. 2003). Biotic and abiotic elements within boundary change in gradient from one system to another (Cadenasso et al. 1997; Fagan et al. 2003). In addition, the habitat heterogeneity and edge influence apparently present within the landscape boundary (Cadenasso and Pickett 2001). Many studies have been carried out in different types of boundaries and different regions with the aim of estimating the distance of edge influence (DEI). In general, the DEI can be detected in terms of biotic characteristics in different types of forest (Li et al. 2007). DEI namely the width of edge influence indicates the distance that some change penetrates into habitats. DEI may be wide or narrow, depending on the gradient of change between patches. Studies on ecological processes across landscape boundaries are needed in developing strategies for restoring and managing agroforestry systems (Laurance et al. 2001; Weathers et al. 2001; Belnap et al. 2003). Clarifying soil moisture distribution across agroforestry provides a basis for studies on distribution characters of biodiversity (Bider 1968; Meng et al. 2003) and soil nutrients (Peterjohn and Correll 1984; Fu et al. 1998) of forest boundaries.

At the middle or small scales, the quantitative determination methods of landscape boundaries were mainly principal component analysis, cluster analysis, β diversity index (Whittaker et al. 1979; Wilson and Mohler 1983), moving split-window (Wierenga et al. 1987; Choesin and Boerner 2002), DEI analysis (Chen, 1996; Saunders, 1999), geographic information system spatial analysis (Krummel et al., 1987), and geostatistics (Schlesinger et al. 1996; Li 2001). In this study, we examined soil moisture content within three agroforestry landscape boundaries to analyze the spatial and temporal characteristics of soil moisture, and to determine the DEI of soil moisture. The objectives of the study are to elucidate the distribution and variation patterns of soil moisture across different types of sloping agroforestry landscape boundaries in different seasons and to provide suggestions for managers in their land-use plans.

Material and methods

The study was conducted in Mafang Forestry Center, Yongshou, Shannxi Province (108°08′E, 34°49′N, and 1 276 m above sea level). Its extreme highest air temperature was 38.9°C, and the extreme lowest -18.0°C. Mean annual precipitation is 600 mm, with more than 60% occurring in July to September. Annual potential evaporation reaches approximately 1 000 mm. Frost-free period is 210 days. Annual sunshine is 2 166.2 h. The annual active accumulated temperature above 10°C (≥10°C) is 3 476.3°C. The area belongs to the temperate continental monsoon climate. The soil is loessial soil developed from loess parent material. The natural vegetation of the study site has been seriously destroyed. In order to protect the environment and promote agricultural production, trees were planted extensively during the 1970s and 1980s. The dominant plantations are *Robinia pseudoacacia*, *Pinus tabulaeformis* and *Caragana microphylla*. The dominant herbaceous species are *Stipa breviflora*, Leymus secalinus, Heteropappus hispidus, Artemisia mongolica, *Bothriochloa ischaemum, Potentilla chinensis* and *Carpesium divaricatum*. Three major agroforestry systems formed in the landscape are forest-grassland, forest-cropland and shelterbelt-cropland.

We established three plots (40 m×30 m) on representative forest-grassland, forest-cropland, and shelterbelt-cropland systems. The tree species in all three types of agroforestry landscape boundaries is *Robinia pseudoacacia*. The crops planted in cropland were wheat (*Triticum aestivum*) and were harvested in June. The grasses growing in forest-grassland were *Stipa breviflora*. The shelterbelt was about 32 m in width. The basic information of these plots is shown in Table 1.

Table 1. Stand characteristics for three investigated boundaries

Boundary types	Aspect	Slope (°)	Age (year)	Density(trees·ha^{-1})	DBH (cm)	Average height (m)	Canopy density (%)
Forest-grassland	S	5	15	2400	8.6	8.0	75
Forest-cropland	S	3	25	2800	12.5	13.0	60
Shelterbelt-cropland	E	4	10	4800	5.4	7.8	80

Soil moistures were measured once in both the middle and the last ten-day of each month from March to October in 2005. No soil moisture samples were measured during January–February and November–December due to the frozen soil. Three line transects with 10 m interval were established perpendicularly to the forest edge. Then, along the direction parallel to the forest edge, we placed line transects at the interior and exterior of forest edge with intervals of 0, 0.2, 0.5, 1, 2, 3 and 5 H (H: mean height of trees). Soil was sampled at the intersection. A soil auger was used to sample soil from 0–10, 10–30, 30–50, 50–70, 70–90 and 90–110 cm layers. The soil moisture content was measured in the laboratory with oven-drying method (105°C) for 12 h. The sampling points at each line for forest-grassland, forest-cropland and shelterbelt-cropland landscape boundaries were 13, 9 and 9, respectively.

The DEI of soil moisture across three landscape boundaries

was estimated through variance analysis and Tukey's test using the ANOVA procedure from SAS 8.1 (SAS Institute, 2000). The method to estimate DEI was as follows. By calculating different depths of soil moisture mean values at different positions across each agroforestry boundary, multiple comparisons could be conducted. The determinations of DEI were depended on whether the differences of different depths of soil moisture in different positions were significant. Near the edge, if the difference of soil moisture in some positions was not significant for a depth across one of three boundaries, the distance between two end positions was the DEI. This method can be applied to determine DEI for different depths of different boundaries.

Results

Vertical variations of soil moisture in three landscape boundaries

Soil moisture in three types of agroforestry landscape boundaries had similar characteristics in the vertical distribution within 0−110 cm depth (Table 2). Soil moisture decreased with soil depth increasing, suggesting that soil moisture was mainly from the precipitation. With soil depth increasing, variation of soil moisture content became smaller among different sampling points across the year. According to the classification method of soil moisture in vertical level in loess region (Jia et al. 1997), the vertical variation characteristics of soil moisture in three types of agroforestry landscape boundaries were as follows: 0–10 cm soil layer was rapidly variable layer, 10–30 cm layer was active layer, 30–70 cm soil layer was secondarily active layer and 70–110 cm soil layer was relatively stable layer (Table 2).

Horizontal variations of soil moisture in three landscape boundaries

Different types of landscape boundaries represented different structures of land use, so studying the soil moisture characteristics was equal to studying the soil moisture effects of different structures of land use. The difference of soil moistures at 0−110 cm depth among three different structures of land use were significant not only in dry season ($p < 0.01$), but also in rainy season ($p < 0.05$) and spring stable season ($p < 0.01$) (Table 3)

Table 2. Statistical characters of different layers of soil moisture at different types of boundaries during March to October of 2005

Boundary types	Depth (cm)	Mean soil moisture ($g \cdot kg^{-1}$)	Standard deviation	Coefficient of variance (CV)	Levels
Forest-grassland	0−10	189	4.96	0.26	Rapidly variable layer
	10−30	184	3.60	0.20	Active layer
	30−50	183	2.60	0.14	Secondarily active layer
	50−70	179	2.03	0.11	
	70−90	178	1.77	0.10	Relatively stable layer
	90−110	178	1.37	0.08	
Forest-cropland	0−10	181	5.84	0.32	Rapidly variable layer
	10−30	173	4.43	0.26	Active layer
	30−50	170	3.44	0.20	Secondarily active layer
	50−70	167	2.45	0.15	
	70−90	163	1.94	0.12	Relatively stable layer
	90−110	162	1.59	0.10	
Shelterbelt-cropland	0−10	184	5.70	0.31	Rapidly variable layer
	10−30	182	3.46	0.19	Active layer
	30−50	179	2.79	0.15	Secondarily active layer
	50−70	172	2.68	0.13	
	70−90	172	1.89	0.11	Relatively stable layer
	90−110	166	1.49	0.09	

Table 3. Influence of different boundaries on soil moisture in 0−110 cm depth

Influence factor	df	In spring of April		In dry season of June		In rainy season of August	
		F	*P*	*F*	*P*	*F*	*P*
Boundary types	2	22.54	0.0016	34.92	0.0005	5.29	0.0473

Among the three boundaries, soil moisture at 0–110 cm depth of forest-grassland landscape boundary was the highest in dry season (June), while there was no difference in soil moisture between the forest-cropland and shelterbelt-cropland landscape boundaries (Fig. 1). The main reason was that the wheat crop used much water before the wheat was harvested in forest-cropland or shelterbelt-cropland boundaries. For all three agroforestry landscape boundaries, soil moisture in rainy season (August) was higher than in any other seasons. The soil moisture of forest-cropland and shelterbelt-cropland landscape boundaries was higher than that of forest-grassland landscape boundary in rainy season, while the difference of soil moisture was not found between forest-cropland and shelterbelt-cropland landscape boundaries, mainly because soil moisture increased with precipitation and the grassland vegetation used a great deal of soil water,

then soil moisture in grassland was lower than those of croplands which had low vegetation cover. After that, less precipitation occurred, therefore, soil water content was never recovered to the level of rainy season. In the relatively stable period (April), the forest-grassland landscape boundary had the highest soil moisture in 0−110 cm depth, and the difference of soil moisture was not significant between forest-cropland and shelterbelt-cropland systems.

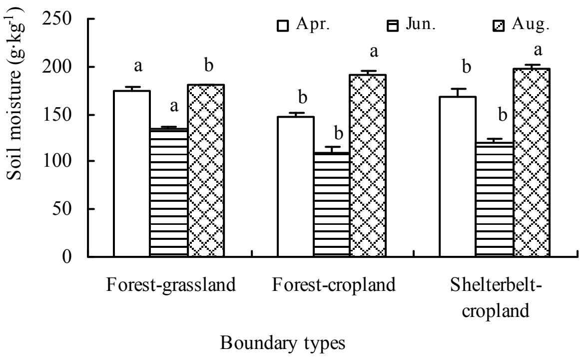

Fig. 1 Soil moisture at 0−110 cm depth in different boundaries

Different letters indicate significant difference of soil moisture among different boundary types at same sampling time (*t* test, $P < 0.05$).

Monthly variations of soil moisture in three landscape boundaries

There were significant differences of soil moisture among different sampling times in all the three agroforestry landscape boundaries (Table 4). The monthly variations of soil moisture at 0–110 cm depth across three types of agroforestry landscape boundaries basically indicated "V" shape; soil moisture gradually decreased from February to June, increased from June to September, and decreased again in October (Fig. 1). These monthly variations of soil moisture were closely related to variation of precipitation at the site. The precipitation during the period of May and June was lower, and soil moisture was the lowest (Fig. 2). From July to September the precipitation was the highest, so was the soil moisture. The precipitation was least in March and April, but soil moisture was not the lowest because soil retained the water in winter due to the snowfall and lower evaporation. The consistence of the monthly variation of soil moisture and the precipitation suggests that soil moisture within 0−110 cm soil depth is mainly controlled by the precipitation.

Table 4. Influence of seasons on soil moisture in 0−110 cm depth

Influence factor	df	Forest-grassland		Forest-cropland		Shelterbelt-cropland	
		F	*P*	*F*	*P*	*F*	*P*
Seasons	7	101.87	0.0001	48.62	0.0001	103.03	0.0001

The soil moisture in each of three agroforestry landscape boundaries was not significantly different between May and June when the soil moisture was the lowest in the year and was significantly different with other months. The main reason was the less precipitation and more evaporation in this period. Water deficit was more severe in May or June in this area. The soil moistures in each of three boundaries in July, August, September and October were not significantly different from each other due to the rainy season compensation period. Soil moistures were not significantly different between March and April. We could consider them as a group and call them of relatively stable period of the spring, when the soil moisture was more than in the dry season and lower than in the rainy season, which was relatively stable. Therefore, we classified the seasonal variations of soil moisture into three periods: dry season deficit period, rainy season compensation period and spring relatively stable period. This classification was consistent with the results of previous studies on seasonal variations of soil moistures in Loess Plateau area (Zhang and Lu 1993; Jia et al. 1997; Chen et al. 2003). On the basis of the classification of three periods of the soil moisture, we selected April, June and August as the representatives of relatively stable period, dry season deficit period and rainy season compensation period, respectively, to further analyze the distribution characteristics of soil moisture across different agroforestry landscape boundaries.

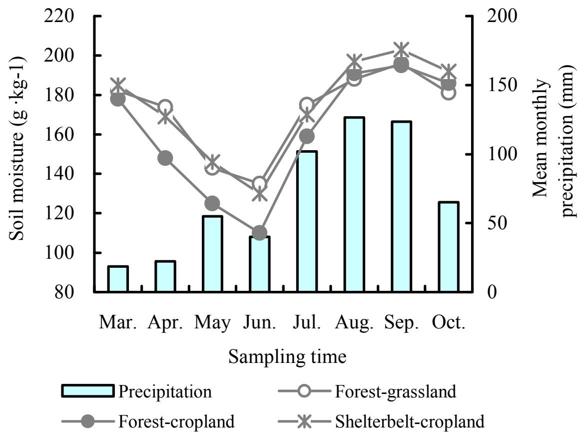

Fig. 2 Seasonal variations of soil moisture at 0−110 cm depth in three boundaries

Horizontal distribution of soil moisture across different types of landscape boundaries

We took forest-grassland boundary as example (Fig. 3), as the patterns of horizontal distribution of soil moisture across three types of landscape boundaries were similar. In spring season (April), vegetation growth depleted soil water quickly from the top soil. On the other hand, the evaporation from top soil is large. Therefore, soil moisture content was lowest at 0−10 cm soil layer and followed by 10−30 cm soil layer (Fig. 3a). With soil temperature increasing, deep roots activity increased and accessed soil water from 30 cm to 110 cm soil layer gradually. By June, trees absorbed more water in entire soil profile than grasses due to deeper roots of trees, whereas grasses used water in soil layer of 0−90 cm. We found more variation of soil moisture among

different soil layers in grass patch than in forest patch. This trend was reversed in rainy season (August), because precipitation recharged only in the top soil and trees still grew vigorously. The horizontal distributions of soil moisture among different layers indicated “W” form (in April), line form (in June), wave form (in August) in forest patch, and wave form (in June), line form (in August) in grass patch, and scoop form (in August) in forest-grassland boundary.

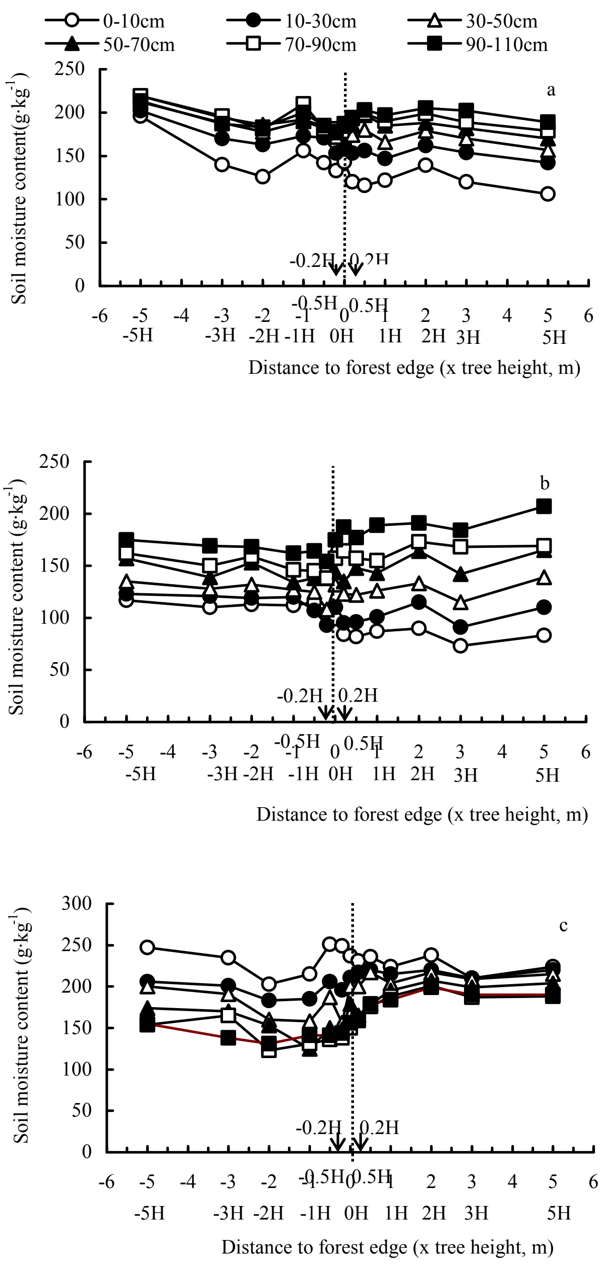

Fig. 3 Horizontal distributions of soil moisture with different depth at forest-grassland boundary. a: In spring (April); b: In dry season (June); c: In rainy season (August). “+” denotes the place of exterior forestland; “–“denotes the place of interior forestland

Edge influence depth of soil moisture across different types of landscape boundaries

In dry season, the DEI of soil moisture at soil layer of 0−10 cm across three types of agroforestry landscape boundaries was easy to determine. In forest-grassland or forest-cropland landscape boundaries, the difference of soil moisture from 0.2 H exterior (H, average height of trees) to 0.2 H interior of the forest was not significant, but was significant compared with other sampling positions (Table 5); therefore, the location from the 0.2 H exterior to 0.2 H interior were considered as the location of DEI of soil moisture in 0−10 cm soil layer across the two landscape boundaries. Similarly, the location of DEI in 0−10 cm soil layer across shelterbelt-crop landscape boundaries was from 0.2 H exterior to 0.5 H interior of the forest. However, the DEI of soil moisture in other layers across three types of boundaries was unable to determine exactly.

Table 5. Mean soil moisture content at 0−10 cm soil layer on different sites of three kinds of landscape boundaries in June together with variance and Tukey’s test

Distance to edge (m)	Mean soil moisture in forest-grassland boundary (g kg^{-1})	Mean soil moisture in forest-cropland boundary (g kg^{-1})	Mean soil moisture in shelterbelt-cropland boundary (g kg^{-1})
5 H	83cd	–	–
3 H	73d	–	–
2 H	90bcd	41d	59d
1 H	87bcd	51d	69bcd
0.5 H	82cd	62cd	64bcd
0.2 H	84bcd	78bc	73abcd
0 H	99abc	93ab	89a
-0.2 H	104ab	85bc	79abc
-0.5 H	115a	117a	80ab
-1 H	112a	98ab	63cd
-2 H	113a	73bcd	62d
-3 H	110a	–	–
-5 H	117a	–	–
Mean value	99	78	71
F Value	6.35**	11.32**	3.04*

Values followed by the different letter within a column are significantly different at $p < 0.05$. *, ** Significant at $p = 0.05$ and $p = 0.01$, respectively.

In the rainy season, the DEI of soil moisture at different layers (0−10, 10−30, 30−50, 50−70, 70−90, 90−110, 0−110 cm) was well determined. At the depth of 0−110 cm (Table 6), the difference of soil moisture from 0.2 H exterior to 0.5 H interior of the forest across three types of agroforestry was not significant, but was significant when compared with other locations. Therefore we considered the 0.2 H exterior to 0.5 H interior as the location of the DEI in soil moisture within 0−110 cm depth across three agroforestry landscape boundaries. However, the DEI of soil

moisture in three types of landscape boundaries in spring was difficult to determine.

Table 6. Mean soil moisture content in depth of 0−110 cm on different positions of three kinds of landscape boundaries in August together with variance and Tukey's test

Distance to edge (m)	Mean soil moisture in forest-grassland boundary ($g \cdot kg^{-1}$)	Mean soil moisture in forest-cropland boundary ($g \cdot kg^{-1}$)	Mean soil moisture in shelterbelt-cropland boundary ($g \cdot kg^{-1}$)
5 H	207ab	–	–
3 H	201abc	–	–
2 H	214a	212a	207ab
1 H	202abc	210a	201abc
0.5 H	201abc	204ab	209a
0.2 H	189bcd	189bc	195abcd
0 H	189bcd	173cd	193abcd
-0.2 H	172de	187bc	189bcd
-0.5 H	178de	175cd	188bcd
-1 H	159e	168d	185cd
-2 H	159e	197ab	176d
-3 H	183cd	–	–
-5 H	190bcd	–	–
Mean value	188	191	194
F Value	5.60^{**}	8.09^{**}	3.34^{*}

The Values followed by the different letter within a column are significantly different at $p < 0.05$. *, ** Significant at $p = 0.05$ and $p = 0.01$, respectively.

Discussion

Agroforestry is a compound ecosystem consisted of cropland/grassland and forest patches. The biotic and abiotic information in the boundary zone between them is very important to understand the agroforestry systems. Although soil moisture distribution in cropland/grassland or in forest ecosystem has been reported previously (Zhang and Lu 1993; Jia et al. 1997; Chen et al. 2003; Li et al. 2005; Muthuri 2009), the results in this study fill the information gap how does soil moisture change under the boundary of two ecosystems. Previous studies (Wang and Li 1995; Jia et al. 1997) in single ecosystems (cropland, grassland or forest) showed that the rapidly variable layer of soil moisture generally lied in 0−20 cm or 0−50 cm depth, active layer lied in 20−50 cm or 20−100 cm, secondary active layer lied in 50−100 cm or 100−120 cm, the location of stable layer was deeper. However, the vertical stratification of soil moisture across three types of agroforestry became shallow, and the scale lessened. The variation in soil moisture beneath 70 cm depth was stable, suggesting that the soil moisture in compound agroforestry ecosystems was stable than in single ones. Our results indicated that the monthly variations in soil moisture of agroforestry landscape boundaries and the soil moisture at depth of 0−110 cm were mainly from precipitation, which confirmed the patterns of previous studies (Zhang and Lu 1993; Jia et al. 1997; Chen et al. 2003; Moreno 2008). In addition, it was found that the soil moistures across forest-grassland landscape boundary were higher than those across forest-cropland boundary and shelterbelt-cropland boundary whenever in spring (relatively stable period) or in dry season (deficit period). Therefore, forest-grassland may be a better land use pattern to conserve soil water in dry loess region, which could also provide scientific evidence to the practice of returning cropland to forestland and grassland in western China.

Many studies demonstrated that the land use structure could influence the soil moisture. Fu (1999) studied the horizontal distribution of soil moisture under three types of land use structure of loess hilly region. The results revealed that the horizontal distribution of soil moisture under different land use structure systems indicted "W", "V" or "U" forms. Li (2005) also considered that the horizontal distribution of soil moisture in a boundary system consisting forest and prickly ash (*Zanthoxylum bungeanum*) land showed "W" and "V" forms. The results from this study were different with their results. It was considered that the distribution patterns of soil moisture varied temporally with different forms (line, wave, scoop, and "W") among different soil layers and different landscape boundaries. Soil moistures are affected by land use pattern and land spatial structure, meanwhile they are the result of integrated interaction of various ecological factors such as terrain. The difference in soil moisture between shallow soil layer and deep soil layer is obvious, so clarifications of soil moisture patterns by studying less layers or integrating the mean levels of various layers are generally inaccurate. The stereo-analysis of different layers should be conducted in future studies.

Many methods had been tried to quantitatively determine the DEI across landscape boundaries (Matlack 1993; Fraver 1994; Cancino 2005). Li et al. (2005) determined the DEI of soil moisture in prickly ash land−coniferous forest boundaries through the moving split-window method; their study aimed at the soil moisture only in shallower layer (0−10 cm). It was known that soil moisture in surface layer varied acutely and is easily influenced by the environment, which was different with the soil moisture of deeper layer. The present study successfully determined the DEI of soil moisture at depth of 0−10 cm in dry season (June) and 0−110 cm depth in rainy season (August) across three types of agroforestry. However, the DEI of soil moisture at different layers could not be determined in spring (April). The main reason could be the higher soil moisture in favor of the DEI's determination and the lower temperature against the DEI's determination by affecting the soil moisture. Surely the determination and dynamic mechanism of the DEI of soil moisture at different layers across agroforestry landscape boundaries need to be further studied.

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